NATIONAL BUREAU OF STANDARDS REPORT

7834

STANDARDIZATION OF THERMAL EMITTANCE MEASUREMENTS

PROGRESS REPORT No. 17

October 1 - December 31, 1962

Contract No. DO (33-616) 61-02
Task No. 73603

AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NBS

U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to government agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. Research projects are also performed for other government agencies when the work relates to and supplements the basic program of the Bureau or when the Bureau's unique competence is required. The scope of activities is suggested by the listing of divisions and sections on the inside of the back cover.

Publications

The results of the Bureau's research are published either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau publishes three periodicals available from the Government Printing Office: The Journal of Research, published in four separate sections, presents complete scientific and technical papers; the Technical News Bulletin presents summary and preliminary reports on work in progress; and the Central Radio Propagation Laboratory Ionospheric Predictions provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of nonperiodical publications: Monographs, Applied Mathematics Series, Handbooks, Miscellaneous Publications, and Technical Notes.

A complete listing of the Bureau's publications can be found in National Bureau of Standards Circular 460, Publications of the National Bureau of Standards, 1901 to June 1947 ($1.25), and the Supplement to National Bureau of Standards Circular 460, July 1947 to June 1957 ($1.50), and Miscellaneous Publication 240, July 1957 to June 1960 (includes Titles of Papers Published in Outside Journals 1950 to 1959) ($2.25); available from the Superintendent of Documents, Government Printing Office, Washington 25, D.C.

NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT
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The two phases of this project are conducted under the supervision of the following persons, who have approved this report.

Horace M. Joseph Horace M. Joseph
Electronic Engineer, Data Processing Systems Division

W N Harrison William N. Harrison - Coordinator
Chief, Metallic Building Materials Section, Building Research Division

to

AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
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*See footnote on page 1.

NOTICES

I. SUMMARY *

Most of the work during the report period was concentrated on improvement and overhaul of the data-processing attachment. By the end of the period most of the malfunctions had been corrected, but the equipment was still not functioning correctly in all respects.

A computer code was written to facilitate checking of the performance of the data-processing attachment.

II. INSTRUMENTATION

Spectrometer Maintenance

In order to ensure operation of the spectrometer at peak efficiency, all of the mirrors were removed, carefully cleaned and replaced. The entire optical system was then realigned. After this had been done, it became apparent that a diminution in sensitivity of the vacuum thermocouple detector required its replacement. A new detector was installed, and the removed detector returned to the factory for repair.

As a preliminary step to extending the wavelength range of experimental work to 38 microns, a new thermocouple detector having approximately four times the sensitivity of the one now used was ordered.

III. DATA-PROCESSING ATTACHMENT

The manufacturer had been informed of the deficiencies in the data-processing attachment, and sent an engineer to the Bureau to correct them. In the main, the difficulties consisted of unstable circuits which resulted in drift from the calibration settings of potentiometers controlling corrections of the zero and 100-percent lines. The trouble was found to be in the digital portions of the circuits. A number of changes were made to improve these functions. A mechanical difficulty, binding of the gears in in the correcting potentiometer drive mechanism, was also found and corrected.

Following these adjustments, the data-processing equipment operated satisfactorily for a time, after which intermittent trouble developed, which was manifested as unequal response of the stepping motors, to signals calling for change in one direction as compared to the other. This effect was found in both correcting circuits, and was traced to overheating of the motor-drive transistor, indicating excessive current through it. Normally the transistor should be kept at cutoff when it is not in operation, but continuous overheating indicated the cutoff was not effective. The difficulty could arise from leakage, from a defect in the power transistor, incorrect bias in the preceding driver stage, improper circuit design, or a combination of causes. Each of these possibilities is being checked.

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* The fifteenth quarterly progress report covered the period Jan. 1 - Mar. 31, 1962. Work done during the period April 1 - December 31, 1962 was covered and included in the summary report for the period July 1, 1958 through Oct. 31, 1962, WADC TR 59-510 Pt IV, which constitutes the sixteenth progress report.

Some of the difficulties with the data-processing equipment were aggravated by noise in the spectrometer amplifier. Efforts to find a preamplifier with a lower noise level than that now used, have not so far been successful.

During a period of satisfactory operation the equipment was checked by use of the reference blackbody furnace and sector-disc attenuator simulating a graybody specimen having an emittance equal to the known transmission factor of 0.75. Curves were obtained which represented a graybody spectral distribution within ± 0.01 of the known correct value over the spectral range of 1 to 15 microns.

The data-processing attachment has provision also for making punched-tape records that can be fed into separate computers to obtain various types of information. Use can be made of the punched-tape records to test the functioning of the equipment as follows: In addition to digitized records of the "zero line", the "100% line" and the uncorrected spectral emittance curve of the specimen, a fourth set of values is recorded on the punched tape, representing the emittance curve of the specimen as corrected concurrently with the test, by use of the magnetic tape, and recorded on the strip chart. This operation requires separate tests on the specimen, with and without correction.

During the report period a computer program was designed so that, from the four-channel punched-tape, the computer would: (1) apply corrections to the uncorrected emittance data, based on the "100% line" and "zero line" records, (2) compare the resulting corrected emittance values with the corresponding corrected values recorded on the punched tape during test through functioning of the magnetic tape, and (3) record the algebraic differences between the two sets of independently corrected data.

The computer program was tried, and was found to function, so that it could be used for the intended purpose. Several tapes had been recorded, ready for processing, at the end of the report period.

IV. WORKING STANDARDS OF NORMAL SPECTRAL EMITTANCE

Working standards of normal spectral emittance having low, intermediate and high emittance, respectively, were prepared, calibrated and transmitted to the Physics Laboratory, A.S.D., prior to the start of the current report period.

Detailed instructions for the handling and use of these standards were prepared and transmitted to the Applications Laboratory, A. S. D., during the current report period.

V. EQUATIONS

The formulas for reflectivity were rewritten using new parameters which are combinations of the original parameters. An analysis of the equations indicated that the new parameters are more directly related to the geometric properties of the calculated reflectivity curve, and it is hoped that their use will facilitate the fitting of the observed reflectivity data. Existing programs were modified to permit use of the new parameters, and exploratory calculations were continued.

VI. WAVELENGTHS FOR 100 SELECTED ORDINATE COMPUTATIONS

The rigorous method of computing total normal emittance from spectral data may be expressed mathematically as follows:

$$E_{ts} = \frac{\int_0^\infty \epsilon_{b\lambda} E_{s\lambda}\, d\lambda}{\int_0^\infty \epsilon_{b\lambda}\, d\lambda} \tag{1}$$

where E_{ts} = total normal emittance of specimen

$\epsilon_{b\lambda}$ = rate of energy emission(radiant flux), per unit area, from a blackbody at the temperature of the specimen, within the wavelength interval λ to $(\lambda + d\lambda)$.

$E_{s\lambda}$ = normal spectral emittance of the specimen at wavelength λ.

All computations from data are based upon finite intervals of wavelength, $\Delta\lambda$.

The following equation applies:

$$E_{ts} \cong \frac{\sum_{\lambda_1}^{\lambda_2} \epsilon_{b\lambda} E_{s\lambda} \Delta\lambda}{\sum_{\lambda_1}^{\lambda_2} \epsilon_{b\lambda} \Delta\lambda} \tag{2}$$

λ_1 and λ_2 being selected to include substantially all of the flux emitted by a blackbody radiator at the test temperature.

In the weighted ordinate method, uniform values of $\Delta\lambda$ are used, and each value of $E_{s\lambda}$ must be weighted by a factor proportional to $\epsilon_{b\lambda}$. This value of $\epsilon_{b\lambda}$ represents the area, within the wavelength interval λ to $(\lambda + \Delta\lambda)$, under the spectral distribution curve of radiant flux, from unit area of a blackbody radiator, at the test temperature.

In the 100-selected-ordinate method, the area under the spectral distribution curve for the radiant flux from a blackbody radiator at the test temperature is divided into 100 equal slices. The 100 selected ordinates are then the 100 median wavelengths for the 100 areas. In this case $\Delta\lambda$ varies, but the quantity $\epsilon_{b\lambda}\Delta\lambda$ is held constant at 0.01. Under these conditions equation (2) can be rewritten:

$$E_{ts} \cong 0.01 \sum_{\lambda_1}^{\lambda_{100}} E_{s\lambda} \tag{3}$$

In practice, any desired degree of precision in the computation of E_{ts} can be attained by either method by taking a sufficient number of ordinates. With any given number of ordinates, the computation error will be less by the selected ordinate method than by the weighted ordinate method. With solids, whose spectral emittance curves do not normally have sharp peaks or valleys, the 100 selected ordinate method gives values that have no significant computation error from this source.

The wavelengths representing the 100 selected ordinates were computed for temperatures of 600, 700, 800, 900, 1000, 1100, 1200, 1300 and 1400°K, and are given in Table I.

The 100 selected ordinates for temperatures of 800°, 1100°, 1300° and 1400°K were converted to digital form and punched on paper tape for use with the data-processing attachment to the normal spectral emittance equipment.

TABLE I

WAVELENGTHS FOR COMPUTATION OF TOTAL EMITTANCE
FROM SPECTRAL DATA BY THE 100-SELECTED ORDINATE METHOD

λ in Microns at Temperature in ^{o}K of

%1/	λT $\mu ^{o}K$	600	700	800	900	1000	1100	1200	1300	1400
.5	1322	2.203	1.889	1.652	1.469	1.322	1.202	1.102	1.017	.944
1.5	1534	2.557	2.191	1.918	1.704	1.534	1.395	1.278	1.180	1.096
2.5	1662	2.770	2.374	2.078	1.847	1.622	1.511	1.385	1.278	1.187
3.5	1762	2.937	2.517	2.020	1.958	1.762	1.602	1.468	1.355	1.258
4.5	1846	3.077	2.637	2.308	2.051	1.846	1.678	1.538	1.420	1.318
5.5	1920	3.200	2.743	2.400	2.133	1.920	1.745	1.600	1.477	1.371
6.5	1989	3.315	2.841	2.486	2.210	1.989	1.808	1.657	1.530	1.424
7.5	2052	3.420	2.931	2.565	2.280	2.052	1.865	1.710	1.578	1.466
8.5	2111	3.518	3.016	2.639	2.346	2.111	1.919	1.759	1.624	1.508
9.5	2168	3.613	3.097	2.710	2.409	2.168	1.971	1.806	1.668	1.549
10.5	2222	3.703	3.174	2.778	2.469	2.222	2.020	1.852	1.709	1.587
11.5	2274	3.790	3.249	2.842	2.527	2.274	2.067	1.895	1.749	1.624
12.5	2325	3.875	3.321	2.906	2.583	2.325	2.114	1.937	1.788	1.661
13.5	2374	3.957	3.391	2.968	2.638	2.374	2.158	1.978	1.826	1.696
14.5	2423	4.038	3.461	3.029	2.692	2.423	2.203	2.019	1.864	1.731
15.5	2470	4.117	3.529	3.088	2.744	2.470	2.245	2.058	1.900	1.764
16.5	2517	4.195	3.596	3.146	2.797	2.517	2.288	2.097	1.936	1.798
17.5	2563	4.271	3.662	3.204	2.848	2.563	2.330	2.136	1.972	1.831
18.5	2609	4.348	3.727	3.261	2.899	2.609	2.372	2.174	2.007	1.864
19.5	2654	4.423	3.792	3.318	2.949	2.654	2.413	2.212	2.042	1.896
20.5	2698	4.496	3.854	3.372	2.998	2.698	2.453	2.248	2.075	1.927
21.5	2743	4.571	3.919	3.429	3.048	2.743	2.494	2.286	2.110	1.959
22.5	2787	4.645	3.982	3.484	3.097	2.787	2.534	2.322	2.144	1.991
23.5	2831	4.718	4.044	3.539	3.146	2.831	2.574	2.359	2.178	2.022
24.5	2876	4.793	4.109	3.595	3.196	2.876	2.615	2.397	2.212	2.054
25.5	2920	4.866	4.172	2.650	3.244	2.920	2.655	2.433	2.246	2.086

TABLE I - continued

%[1/]	λT $\mu\,^{o}K$	600	700	800	900	1000	1100	1200	1300	1400
		λ in Microns at Temperature in ^{o}K of								
26.5	2964	4.940	4.234	3.705	3.293	2.964	2.695	2.470	2.280	2.117
27.5	3008	5.013	4.297	3.760	3.342	3.008	2.735	2.507	2.314	2.149
28.5	3052	5.086	4.360	3.815	3.391	3.052	2.775	2.543	2.348	2.180
29.5	3097	5.161	4.424	3.871	3.441	3.097	2.815	2.581	2.382	2.212
30.5	3141	5.235	4.487	3.926	3,490	3.141	2.855	2.617	2.416	2.244
31.5	3186	5.310	4.552	3.982	3.540	3.186	2.896	2.655	2.451	2.276
32.5	3231	5.385	4.616	4.039	3.590	3.231	2.937	2.692	2.485	2.308
33.5	3277	5.461	4.682	4.096	3.641	3.277	2.979	2.731	2.521	2.341
34.5	3323	5.538	4.747	4.154	3.692	3.323	3.021	2.769	2.556	2.374
35.5	3369	5.615	4.813	4.211	3.743	3.369	3.063	2.807	2.592	2.406
36.5	3415	5.691	4.879	4.269	3.794	3.415	3.105	2.846	2.627	2.439
37.5	3462	5.770	4.946	4.328	3.847	3.462	3.147	2.885	2.663	2.473
38.5	3510	5.850	5.014	4.388	3.900	3.510	3.191	2.925	2.700	2.507
39.5	3558	5.930	5.083	4.448	3.953	3.558	3.235	2.965	2.737	2.542
40.5	3607	6.011	5.152	4.509	4.008	3.607	3.279	3.006	2.775	2.576
41.5	3656	6.093	5.223	4.570	4.062	3.656	3.324	3.047	2.812	2.611
42.5	3706	6.176	5.294	4.632	4.118	3.706	3.369	3.088	2.851	2.647
43.5	3757	6.261	5.367	4.696	4.174	3.757	3.415	3.131	2.890	2.684
44.5	3809	6.348	5.441	4.761	4.232	3.809	3.463	3.174	2.930	2.721
45.5	3861	6.435	5.516	4.826	4.290	3.861	3.510	3.217	2.970	2.758
46.5	3914	6.523	5.592	4.892	4.349	3.914	3.558	3.262	3.011	2.796
47.5	3968	6.613	5.669	4.960	4.409	3.968	3.607	3.307	3.052	2.834
48.5	4023	6.705	5.747	5.029	4.470	4.023	3.657	3.352	3.095	2.874
49.5	4079	6.798	5.827	5.099	4.532	4.079	3.708	3.399	3.138	2.914

TABLE I - continued

λ in Microns at Temperature in ^{o}K of

%1/	λT $\mu\,^{o}K$	600	700	800	900	1000	1100	1200	1300	1400
50.5	4136	6.893	5.909	5.170	4.596	4.136	3.750	3.447	3.182	2.954
51.5	4194	6.990	5.992	5.242	4.660	4.194	3.813	3.495	3.226	2.996
52.5	4254	7.090	6.077	5.318	4.727	4.254	3.867	3.545	3.272	3.039
53.5	4314	7.190	6.163	5.392	4.793	4.314	3.922	3.595	3.318	3.081
54.5	4377	7.295	6.253	5.471	4.863	4.377	3.979	3.647	3.367	3.126
55.5	4440	7.400	6.343	5.550	4.933	4.440	4.036	3.700	3.415	3.171
56.5	4505	7.508	6.436	5.631	5.006	4.505	4.095	3.754	3.465	3.218
57.5	4572	7.620	6.532	5.715	5.080	4.572	4.156	3.810	3.517	3.266
58.5	4640	7.733	6.629	5.800	5.156	4.640	4.218	3.867	3.569	3.314
59.5	4710	7.856	6.729	5.888	5.233	4.710	4.282	3.925	3.623	3.364
60.5	4782	7.970	6.832	5.978	5.313	4.782	4.347	3.985	3.678	3.416
61.5	4856	8.093	6.937	6.070	5.396	4.856	4.415	4.047	3.735	3.469
62.5	4932	8.220	7.046	6.165	5.480	4.932	4.484	4.110	3.794	3.523
63.5	5010	8.350	7.157	6.262	5.567	5.010	4.555	4.175	3.854	3.579
64.5	5091	8.485	7.273	6.364	5.657	5.091	4.628	4.242	3.916	6.636
65.5	5175	8.625	7.393	6.469	5.750	5.175	4.705	4.312	3.981	3.696
66.5	5262	8.770	7.517	6.578	5.847	5.262	4.784	4.385	4.048	3.759
67.5	5351	8.918	7.644	6.689	5.945	5.351	4.865	4.459	4.116	3.822
68.5	5444	9.073	7.777	6.805	6.049	5.444	4.945	4.536	4.188	3.889
69.5	5541	9.235	7.916	6.926	6.157	5.541	5.037	4.617	4.262	3.958
70.5	5641	9.401	8.059	7.051	6.268	5.641	5.128	4.701	4.339	4.029
71.5	5745	9.575	8.207	7.181	6.383	5.745	5.223	4.787	4.419	4.105
72.5	5854	9.756	8.363	7.318	6.504	5.854	5.322	4.878	4.503	4.181
73.5	5968	9.946	8.526	7.460	6.631	5.968	5.425	4.923	4.591	4.263
74.5	6087	10.145	8.696	7.609	6.763	6.087	5.533	5.072	4.682	4.348
75.5	6212	10.353	8.874	7.765	6.902	6.212	5.647	5.176	4.778	4.437

TABLE I - continued

%[1]	λT μ °K	λ in Microns at Temperature in °K of 600	700	800	900	1000	1100	1200	1300	1400
76.5	6343	10.571	9.062	7.929	7.048	6.343	5.766	5.286	4.879	4.531
77.5	6482	10.803	9.260	8.102	7.202	6.482	5.893	5.401	4.986	4.630
78.5	6628	11.046	9.469	8.285	7.364	6.628	6.025	5.523	5.098	4.734
79.5	6783	11.304	9.690	8.479	7.537	6.783	6.166	5.652	5.218	4.845
80.5	6948	11.580	9.926	8.685	7.720	6.948	6.316	5.790	5.345	4.963
81.5	7123	11.871	10.176	8.904	7.914	7.123	6.475	5.936	5.479	5.088
82.5	7311	12.185	10.444	9.139	8.123	7.311	6.646	6.092	5.624	5.222
83.5	7514	12.523	10.735	9.392	8.349	7.514	6.831	6.261	5.780	5.367
84.5	7732	12.886	11.046	9.665	8.591	7.732	7.029	6.443	5.948	5.523
85.5	7969	13.281	11.385	9.961	8.854	7.969	7.245	6.641	6.130	5.692
86.5	8228	13.712	11.755	10.285	9.142	8.228	7.480	6.856	6.329	5.877
87.5	8513	14.188	12.162	10.641	9.459	8.513	7.739	7.094	6.548	6.081
88.5	8829	14.714	12.613	11.036	9.810	8.829	8.026	7.357	6.791	6.306
89.5	9183	15.304	13.119	11.479	10.203	9.183	8.348	7.652	7.064	6.559
90.5	9583	15.971	13.690	11.979	10.648	9.583	8.712	7.986	7.371	6.845
91.5	10042	16.736	14.346	12.552	11.158	10.042	9.129	8.386	7.725	7.173
92.5	10577	17.628	15.110	13.221	11.752	10.577	9.615	8.813	8.136	7.555
93.5	11215	18.524	16.022	14.019	12.461	11.215	10.195	9.345	8.627	8.011
94.5	11996	19.993	17.137	14.995	13.329	11.996	10.878	9.996	9.228	8.569
95.5	12990	21.649	18.558	16.238	14.433	12.990	11.809	10.825	9.992	9.278
96.5	14327	23.877	20.468	17.909	15.919	14.327	13.025	11.939	10.021	10.233
97.5	16295	27.157	23.279	20.369	18.105	16.295	14.814	13.579	12.535	11.639
98.5	19724	32.872	28.178	24.655	21.915	19.724	17.931	16.436	15.172	14.088
99.5	29372	48.951	41.961	36.715	32.635	29.372	26.702	24.476	22.594	20.980

1/ The wavelength λ is chosen so that the indicated percentage of blackbody radiation occurs at wavelengths shorter than the indicated wavelength. Expressed mathematically

$$\frac{\int_0^{\lambda} E_{B\lambda} d\lambda}{\int_0^{\infty} E_{B\lambda} d\lambda} \times 100 = \%$$

U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D. C.

Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics. High Voltage.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics.

Radiation Physics. X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research. Crystal Chemistry.

Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Polymers. Macromolecules: Synthesis and Structure. Polymer Chemistry. Polymer Physics. Polymer Characterization. Polymer Evaluation and Testing. Applied Polymer Standards and Research. Dental Research.

Metallurgy. Engineering Metallurgy. Microscopy and Diffraction. Metal Reactions. Metal Physics. Electrolysis and Metal Deposition.

Inorganic Solids. Engineering Ceramics. Glass. Solid State Chemistry. Crystal Growth. Physical Properties. Crystallography.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials. Metallic Building Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Operations Research.

Data Processing Systems. Components and Techniques. Computer Technology. Measurements Automation. Engineering Applications. Systems Analysis.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Far Ultraviolet Physics. Solid State Physics. Electron Physics. Atomic Physics. Plasma Spectroscopy.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Elementary Processes. Mass Spectrometry. Photochemistry and Radiation Chemistry.

Office of Weights and Measures.

BOULDER, COLO.

Cryogenic Engineering Laboratory. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

CENTRAL RADIO PROPAGATION LABORATORY

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services. Vertical Soundings Research.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Frequency Utilization. Modulation Research. Antenna Research. Radiodetermination.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. High Latitude Ionosphere Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

RADIO STANDARDS LABORATORY

Radio Physics. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time-Interval Standards. Radio Plasma. Millimeter-Wave Research.

Circuit Standards. High Frequency Electrical Standards. High Frequency Calibration Services. High Frequency Impedance Standards. Microwave Calibration Services. Microwave Circuit Standards. Low Frequency Calibration Services.

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